

## BIG BANG AND HEAVY PARTICLES

A.D. DOLGOV

*INFN, sezione di Ferrara, Via Paradiso, 12 - 44100 Ferrara, Italy;*

*ITEP, Bol. Chermushkinskaya 25, Moscow 113259, Russia*

*ICTP, Strada Costiera 11, 31014 Trieste, Italy;*

*E-mail: adolgov@fe.infn.it*

A possibility of existence of ultra-heavy (quasi)stable particles, mechanisms leading to their large life-time, their production in the early universe, and cosmological manifestations are reviewed.

### 1. Introduction

We know from experiment that there are only a few stable particles,  $e$ ,  $p$ ,  $\nu$ , and  $\gamma$  which are relatively light. It is an open question if there exist heavier stable or quasi-stable particles. Possibly they have not yet been discovered because the energies of available accelerators are not large enough for their production. On the other hand, we have “poor man accelerator”, big bang, and believe that in the early universe all kind of particles with the mass of the order of the temperature of primeval plasma, or even considerably higher than that, could be produced. If these particles are stable or long-lived we may hope to see some signatures of them today. Moreover they can be helpful for solution of some cosmological puzzles.

In what follows I am going to address the following questions:

1. Why do we need such heavy (quasi)stable particles, HqSP? (Below we will use for them either this abbreviation or just denote them as  $x$ .)
2. What type of objects can they be?
3. How HqSP could be created in the early universe?
4. What mechanism makes them (quasi)stable?

We do not have rigorous answers to these questions and in many cases one has to rely on reasonable hypotheses or, as is fashionable to say now, conjectures.

### 1.1. *Why may we need them?*

There are several places where existence of HqSP, may help:

If they have mass about  $10^{13}$  GeV and life-time of the order of or larger than the universe age,  $\tau_x > t_U \approx 10^{10}$  years, their decays may solve the mystery of ultrahigh energy cosmic rays<sup>1</sup> observed beyond the Greisen-Zatsepin-Kuzmin cut-off<sup>2</sup>. For recent reviews see e.g.<sup>3</sup>.

A very heavy particle with mass in the range  $10^{12} - 10^{16}$  GeV and either absolutely stable or with life-time larger than the universe age was suggested in ref.<sup>4</sup> as a candidate for the cosmological dark matter.

Heavy long-lived particles, though not as long as the universe age, could be very efficient in baryogenesis if their decay does not conserve baryonic charge. The life-time should be much larger than the inverse Hubble parameter at  $T \sim m_x$ , i.e.  $\tau_x < m_{Pl}/m_x^2$ , to ensure strong deviation from thermal equilibrium but shorter than roughly 1 sec to respect the standard big bang nucleosynthesis.

Charged heavy stable particles could catalyze thermonuclear reactions<sup>5</sup> and make feasible thermonuclear power stations if we find a way to produce or dig them out in sufficiently large quantities.

Even more efficient for power production could be magnetic monopoles efficiently catalyzing proton decay<sup>6</sup>. Finding enough monopoles could solve energy problems for almost infinitely long time, even after the Sun exhausts its nuclear power and dies.

### 1.2. *What kind of objects could they be?*

There are three (or maybe four) logical possibilities:

Normal elementary particles, with the size of the order of their Compton wave length,  $l_x \sim 1/m_x$ . We can take their mass as a free parameter and have to understand why such particles are (quasi) stable despite being heavy. One well known type of heavy (but not very heavy) hypothetical stable (or long-lived) particle is the lightest supersymmetric particle, LSP. They are known to be stable if R-parity is rigorously conserved. Their mass in minimal supersymmetric extension of the standard model is however, not as huge as mentioned above, from  $\sim 100$  GeV up to a few TeV. In this mass range LSP is a good candidates for dark matter particles but it is not excluded that supersymmetry is realized at much higher energy scale and in this case the masses may be much larger.

Magnetic monopoles already mentioned above are not really elementary particles because their size  $1/(\alpha m)$  is much larger than their Compton wave

length. Still they are pretty small. For GUT monopoles with  $m \approx 10^{17}$  GeV the size is about  $10^{-29}$  cm.

Known non-topological solitons are usually very heavy and large and hence we will not consider them as elementary particles.

Interesting objects are mini black holes (BH) with the mass of the order of the Planck mass,  $m_{BH} \sim m_{Pl} = 1.22 \cdot 10^{19} \text{ GeV} = 2.18 \cdot 10^{-5} \text{ g}$ . In multidimensional models with TeV scale gravity <sup>7</sup> the mass of such black holes could be much smaller, down to TeV.

## 2. Stability

### 2.1. Mini black holes

Bigger mass black holes evaporate semi-classically through the Hawking process but nothing is known about quantum mini-BH with mass equal to the Planck mass. For them unknown effects of quantum gravity are 100% important. It is not yet agreed upon if they are stable or not. The answer is probably determined by the ultraviolet behavior of quantum gravity. If the latter is UV-free than mini-BH's could quite possibly be stable.

On the other hand, as the saying goes “anything which is not forbidden is allowed”. It is especially true for quantum field theory and if there is no special law to forbid decay the particle must be unstable. We do not know any such law for mini-BH but the lack of knowledge does not prove that such a law does not exist. If mini black holes are stable and if gravity becomes strong at TeV scale then there must exist stable particles (black holes) with TeV mass.

### 2.2. Magnetic monopoles

Stability of magnetic monopoles is ensured by topology - it is impossible to unwind the gauge field lines at least in 3-dimensional space. It corresponds to conservation of magnetic charge. Though this conservation looks similar to conservation of electric charge, it is not the same. If photon is exactly massless then it is impossible to formulate a consistent theory with non-conserved charge. However, even with massive but very light photon, satisfying experimental bounds on photon mass <sup>8</sup>, the processes with electric charge non-conservation become exponentially strongly suppressed, as  $\exp[-C(E/m_\gamma)^2]$ , where  $E$  is the characteristic energy of the process and  $m_\gamma$  is the photon mass, as is argued in ref.<sup>9</sup>. Hence, most probably, electron would be stable even if electric charge is not conserved. It is unclear

if the same suppression is valid for magnetic monopoles, or in the case of massive (but very light) photons magnetic charge may be non-conserved and magnetic monopoles could quickly decay.

### 2.3. *Heavy elementary particles*

“Normal” decay width of an elementary particle is  $\Gamma_x \sim g^2 m_x$  where  $g$  is a coupling constant characterizing interaction leading to the decay. Usually  $g < 1$  but not outrageously small. Anomalously small or vanishing decay width in all known cases is explained by a conservation law related to an unbroken symmetry, as e.g. the discussed above stability of electron due to conservation of electric charge which, in turn, is related to local  $U(1)$ -symmetry and vanishing mass of the gauge boson, photon.

Stability of another known stable particle, proton, is prescribed to conservation of baryonic charge. The corresponding  $U(1)$ -symmetry is most probably global and is not associated with a gauge boson. An idea of possible long range forces related to baryonic charge was put forward in ref. <sup>10</sup> and similar idea about leptonic charge forces in ref. <sup>11</sup> (for a review see ref. <sup>12</sup>). It was found in these works, however, that a high precision tests of the equivalence principle put very stringent bounds on possible coupling constant of baryo- and lepto- photons:  $\alpha_B < 10^{-47}$  and  $\alpha_L < 10^{-48}$ . Thus, most probably long range forces induced by baryonic and/or leptonic charges are absent. It is believed that global symmetries should be broken by gravity at Planck scale. As was noticed in ref. <sup>13</sup> and later analyzed in <sup>14</sup> formation of a virtual Planck mass black hole would induce proton instability with life-time of the order of

$$\tau_p \sim m_{Pl}^4 / m_p^5 \sim 10^{45} \text{ years.} \quad (1)$$

In the case of TeV gravity the life-time of proton would be tiny,  $\tau_p \sim 10^{-12}$  sec. However, if the black hole formation is suppressed then the same would be true for the proton decay. One may expect exponential suppression of the production of classical objects in elementary particle interactions and, if black hole is indeed such, then gravitationally induced decay would not be effective. If this is true then the accelerator production of TeV mass black holes should be negligible <sup>15</sup>. Thus we are left with the dilemma: either proton leaves  $10^{-12}$  sec or TeV black-holes cannot be produced at accelerators <sup>14</sup>.

Since Planck mass black holes have the size  $r_g \approx 1/m_{BH}$ , i.e. equal to their Compton wave length, they may be considered as elementary particles and their production is most probably unsuppressed. If so, the mass scale of

gravity,  $m_{gr}$ , can be bounded by the long life-time of proton<sup>8</sup>,  $\tau_p > 2.1 \cdot 10^{29}$  years. Using equation (1) we obtain  $m_{gr} > 2 \cdot 10^{15}$  GeV, which is not too far from the normal Planck scale  $10^{19}$  GeV.

Very heavy particles which were introduced for explanation of the observed ultra high energy cosmic rays (UHECR) should have mass about  $10^{13}$  GeV. Their decay, induced by gravity, would have life-time about 1 sec, even with normal huge Planck mass. The same would be true for ultra heavy dark matter particles. Thus such particles could neither produce UHECR, nor make cosmological dark matter.

A possible way to make them stable is to assume that they belong to a non-singlet representation of a local symmetry group  $G$ . Either they are charged with respect to a new  $U'(1)$  group and new “photons”,  $\gamma'$  exist, or there is a new non-Abelian group, similar to QCD, with a high confinement scale. If this group  $G$  is unbroken, then the lightest charged particle must be completely stable. Instability could be induced by a minuscule breaking of  $G$ .

If such ultra-heavy charged particles are completely stable, they nevertheless may create energetic cosmic rays if their positronium-like bound states have been formed in the early universe<sup>16,17</sup> and their annihilation is so slow that the life-time of the corresponding “-onium” is larger than the universe age. However, an explicit realization of this idea seems to meet serious problems.

On the other hand, if gravitational decay is exponentially suppressed by some yet unknown reason then the life-time of such heavy particles could easily be in the required range of  $\tau_x \geq t_U$ . There is no reliable answer to what really takes place and thus any hypothesis is allowed.

One more comment may be interesting here. If the scale of strong gravity is about  $m_{gr} \sim 1$  TeV then the particle with mass  $10^{13}$  GeV and size  $l_x = 1/m_x$  would be inside their Schwarzschild horizon,  $r_g = m_x/m_{gr}^2 = (1/m_x)(m_x/m_{gr})^2 > l_x$  and thus they form black holes. Such black holes would evaporate by the Hawking process and have the life-time

$$\tau_x \sim 0.1 m_x^3 / m_{gr}^4 \approx 10^2 \text{ sec} \left( \frac{m_x}{10^{13} \text{ GeV}} \right)^3 \left( \frac{1 \text{ TeV}}{m_{gr}} \right)^4 \quad (2)$$

This arguments make it very plausible that existence of HqSP particles is not compatible with TeV-scale gravity. Of course, if the considered heavy particles have a conserved gauge charge  $Q_g$ , then such lightest charged black hole would not evaporate and would be absolutely stable. However, even a small mass of the related gauge boson,  $m_g$ , would make evaporation

possible, even if the charge is  $Q_g$  is strictly conserved<sup>18</sup>. In the limit of very small  $m_g$  the life-time of such charged black holes should be of the order  $1/m_g$ . An interesting possibility is a non-minimal gauge non-invariant coupling of the gauge field to the curvature scalar of the form

$$L = g^{\mu\nu} A_\mu^{(g)} A_\nu^{(g)} R \quad (3)$$

Since  $R \sim 1/t_U^2$  the life-time of  $g$ -charged black holes would be always of the order of  $1/H \sim t_U$ .

### 3. Production mechanisms

#### 3.1. Thermal production

All particles with masses smaller or of the order of temperature are abundant in cosmic plasma if thermal equilibrium with respect to them is established. If temperature is small in comparison with the particle mass then their abundance is Boltzmann suppressed. The ratio of massive to massless number densities at  $T < m$  is:

$$n(m)/n(0) \approx (m/T)^{3/2} e^{-m/T} \quad (4)$$

The condition for equilibrium is slow cosmological expansion in comparison with the reaction rate,

$$\dot{n}/n \sim \sigma n > \dot{a}/a \equiv H, \quad (5)$$

where  $\sigma$  is the interaction cross-section,  $a(t)$  is the cosmological scale factor, and  $H$  is the Hubble parameter. The latter is expressed through the total cosmological energy density:

$$H = \frac{8\pi\sqrt{\rho}}{3m_{Pl}} = \frac{8\pi^3 g_*}{90} \frac{T^2}{m_{Pl}} \quad (6)$$

where  $g_*$  is the effective number of relativistic species.

If the universe temperature after inflation was low,  $T^{(in)} < m_x$ , then the heavy  $x$ -particles would not be thermally produced. However, one can outwit the Nature if would-be heavy particles  $x$  were massless at the production time and became massive later as a result of phase transition which made them massive<sup>19</sup>. In such a case the plasma might be populated by heavy particles with  $m > T$  and with the number density equal to that of equilibrium massless particles,  $n \sim T^3$ .

### 3.2. Topological production

Classical objects, i.e. the objects with size bigger than their Compton wavelength,  $l > 1/m$ , probably cannot be efficiently created in thermal bath. For example, magnetic monopoles are produced by the so called Kibble mechanism<sup>20</sup>: in causally disconnected regions the gauge field lines can be arbitrary winded and end up in monopole configuration, roughly one per one Hubble volume,  $H^{-3}$ , or Ginsburg correlation volume,  $(\lambda\eta)^{-3}$ , where  $\eta$  is the vacuum expectation value of the Higgs field and  $\lambda$  is the coupling constant of the quartic self-interaction,  $\lambda(|\phi|^2 - \eta^2)$ .

Topological defects could be formed at the end of inflation at the pre-heating stage<sup>21</sup> because of possible phase transitions (for a review see ref. <sup>22</sup>).

Production of classical objects in particle collisions have not yet been rigorously calculated. There is a common agreement that production of a pair of magnetic monopoles in the reaction  $e^+e^- \rightarrow M\bar{M}$  is exponentially suppressed. On the other hand, monopole annihilation into all possible particles,  $M\bar{M} \rightarrow all$ , is probably quite efficient with the cross-section  $\sigma \sim C/m_M^2$  with a constant coefficient  $C \geq 1$ . This process is probably dominated by a large multiplicity reactions with the number of produced particles of the order of  $1/\alpha \sim 100$ . One may argue that due to time invariance and related detailed balance condition (even an approximate one because of a small breaking of time invariance) the inverse process ( $100\ particles \rightarrow M\bar{M}$ ) would proceed with the same probability and hence thermal production of monopoles would be unsuppressed. On the other hand, it looks quite plausible that in  $M\bar{M}$ -annihilation a very special coherent state of final particles is formed which practically never occurs in thermal bath. If this is true then the annihilation of monopoles would be efficient, while the inverse process would be suppressed by a huge entropy factor.

One may encounter the same or similar problems in formation of black holes in accelerators, discussed above, and in electro-weak baryogenesis<sup>23</sup> which proceeds through formation of classical field configurations, sphalerons. For more detailed discussion and literature see <sup>24</sup>.

### 3.3. Particle production by inflaton field

In the course of inflation the inflaton field  $\Phi(t)$  evolves very slowly but closer to the end the evolution becomes much faster and  $\Phi(t)$ , as any time-dependent field, starts to create particles with which it is coupled. Typically

the produced particles have the masses which are smaller than or comparable to the characteristic frequency of the inflaton variation,  $\omega \sim \dot{\Phi}/\Phi$ . The most favorable situation for particle creation is the regime when  $\Phi$  oscillates around the minimum of its potential:

$$\Phi(t) = \Phi_0(t) \cos(m_\Phi t + \delta) \quad (7)$$

The interaction Lagrangian of  $\Phi$  with usual particles is of the type:

$$L_{int} = g\Phi\bar{\psi}\psi + \lambda\Phi^2\chi^*\chi + \dots \quad (8)$$

where  $\psi$  and  $\chi$  are respectively quantum fermion and boson fields and the inflaton field  $\Phi(t)$  is considered as a classical field. The coupling constants  $g$  and  $\lambda$  are supposed to be small, otherwise self-interaction of the inflaton induced by loop corrections would be unacceptably strong. Hence perturbation theory is applicable for description of the particle production<sup>25</sup>, but only in the case when the masses of the produced particles are smaller than the oscillation frequency,  $\omega = m_\Phi$ . In this case the probability of fermion production per unit time,  $\dot{n}_\psi/n_\Phi$ , is simply the decay width of  $\Phi$ -boson,

$$\Gamma_{pt} = g^2 m_\Phi / 8\pi. \quad (9)$$

The energy of each produced fermion is equal to  $m_\Phi/2$ . The same result would be true for any trilinear coupling  $\Phi\chi_1\chi_2$ . For the quartic coupling of eq. (8) the production probability is  $\dot{n}_\chi/n_\Phi \sim \lambda^2\Phi_0^2/m_\Phi$  and the energy of each produced boson being equal to  $m_\Phi$ . As is mentioned above, these results are true if the masses of produced particles are small in comparison with  $m_\Phi$ . One should keep in mind that the former includes the time dependent contribution from the interaction with  $\Phi$  (8):

$$m_\psi^{(eff)} = m_0 + g\Phi_0(t) \cos(m_\Phi t + \delta), \quad (10)$$

Due to the last term the effective mass of the produced particles rises together with rising amplitude of the classical  $\Phi$ . Because of that the probability of particle production by this field drops down for large field amplitude, a counter-intuitive result. If  $g\Phi_0 > m_\Phi$ , the perturbative approach becomes inapplicable and non-perturbative calculations are necessary. In this case, and for  $m_0 < m_\Phi$ , the productions of fermions is suppressed as<sup>26</sup>:

$$\Gamma \sim \Gamma_{pt} \left( \frac{m_\Phi}{g\Phi_0} \right)^{1/2} \quad (11)$$

Production takes place during a short time interval when the effective mass of  $\psi$  is close to zero. This gives rise to a power law suppression. However, if  $m_0 \gg m_\Phi$  then the particle production is exponentially suppressed,



$\sim \exp[-m_0/m_\Phi]$ . If  $m_0 > m_\Phi$ , but not too much bigger, then the suppression of production would be suppressed by an additional power in the coupling constant because the multi-quantum production would be necessary to respect the energy conservation law.

However, the production of would-be-heavy particles is quite efficient if the same trick as described above is realized: namely, the bare masses of particles are very small initially but after they are produced they acquire large masses by a Higgs type phase transition. On the other hand, as is argued e.g. in ref. <sup>27</sup> heavy fermions with masses up to  $10^{17} - 10^{18}$  GeV could be efficiently produced at the preheating stage, even without such a trick. This statement contradicts the results of ref. <sup>26</sup>, according to which heavy fermions are always much slower produced than massless ones.

Production of bosons could be strongly amplified by the parametric resonance <sup>26,28,29</sup>. In quantum language this resonance can be understood as Bose condensation of the produced particles in the mode  $p^2 = m_\Phi^2/4 - m_\chi^2$  (for the coupling  $\Phi\chi\chi^*$ ). The resonance should be sufficiently wide to keep the produced particles in the resonance mode despite red-shift and possible (self)scattering.

### 3.4. Gravitational particle production

As we mentioned above, a time varying external field can produce elementary particles. This should be true in particular for gravitational field. However, the FRW metric is known to be conformally flat, i.e. after suitable redefinition of coordinates the interval can be rewritten in Minkowskian form with a common scale factor:

$$ds^2 = a^2(\eta, \mathbf{r}) (d\eta^2 - d\mathbf{r}^2) \quad (12)$$

where in spatially flat universe the scale factor  $a$  depends only on conformal time  $\eta$  and not on the space coordinate  $\mathbf{r}$ .

From this property it immediately follows that conformally invariant particles, e.g. massless fermions or vector bosons are not created by cosmological gravitational field <sup>30</sup>. This is true at least classically but quantum corrections, leading to well known triangle trace anomaly<sup>31</sup>, break conformal invariance and allows for production of massless gauge bosons in FRW background <sup>32</sup>. Of course massive particles are not conformally invariant and their production rate is proportional to  $m_x^2$ . Calculations of massive particle production in cosmological background have been done in the 70th <sup>33</sup> and are reviewed in the book <sup>34</sup>. Recently, because of the re-

newed interest to heavy particle production in cosmology, more publications appeared <sup>35</sup> and has been reviewed <sup>22</sup>.

According to the calculations of the quoted papers, the ratio of the energy densities of the produced particles to the total cosmological energy density is

$$\rho_x/\rho_{tot} \sim (m_x/m_{Pl})^2 \quad (13)$$

For comparison particle production due to the trace anomaly gives

$$\rho_{anom}/\rho_{tot} \sim (\alpha\beta)^2 (H_{prod}/m_{Pl})^2 \quad (14)$$

where  $\alpha \sim 1/50$  is the fine structure constant at high energies,  $\beta$  is the leading coefficient of the beta-function, and  $H_{prod}$  is the value of the Hubble constant at the earliest moment of the production; in inflationary model it should be the Hubble parameter at the end of inflation. Anomalous production is operative only for light particles with masses smaller than  $H_{prod}$ . If these particles acquire a large mass later, after some phase transition, anomalous production could be a dominant cosmological source of heavy particles.

Theoretical description of the particle production in cosmology encounters the following problem. The notion of particle depends upon the definition of the vacuum state and particle production is unambiguously described if external field which produces particles disappears at positive and negative time infinities. In this case one can define positive and negative energy states corresponding to particles and antiparticles and use the standard technique with the Bogolyubov coefficients. However, in cosmology the gravitational field does not disappear in initial state, even more it is typically very strong, and definition of vacuum meets serious problems. These problems are related to the nonlocal character of separating of positive and negative energies. In particular, the particle number operator is a nonlocal one. To avoid these problem one may work with local operators e.g. with the energy-momentum tensor,  $T_{\mu\nu}$ . The definitions of pressure and energy densities are unambiguous and one can calculate the time evolution of the latter and a modification of the equation of state of cosmological matter which in turn leads to a change in the expansion regime.

It is interesting in this connection to mention the Unruh effect <sup>36</sup>: an accelerated observer in vacuum would see locally thermal bath of particles with temperature proportional to acceleration. On the other hand if we calculate the total energy-momentum tensor of the system it should be identically zero. It is evidently zero in the original inertial frame and it

remains zero after we make a transformation to the accelerated frame. In these terms the effect is simply redistribution of the total local  $T_{\mu\nu}$  between the vacuum,  $T_{\mu\nu}^{(vac)}$ , and particle,  $T_{\mu\nu}^{(part)}$ , ones in the accelerated frame such that  $T_{\mu\nu}^{(vac)} + T_{\mu\nu}^{(part)} = 0$ .

#### 4. Cosmological impact of HqSP

If the life time of heavy particles is smaller than 1 sec, then they would not play any noticeable role in big bang nucleosynthesis (BBN) and would be practically unnoticeable. The decays of HqSP could create baryon asymmetry of the universe but it is impossible to verify. For larger life-times the effects of their decays could be observable in BBN, CMBR, large scale structure, and, as is mentioned above, in ultra high energy cosmic rays. With very long life-time,  $\tau_x > T_U$ , HqSP could be dark matter particles. Their number density in this case is bounded from above by

$$m_x n_x < 1.5 \text{ keV/cm}^3 \quad (15)$$

i.e.  $n_x < 10^{-20}/\text{cm}^3 (10^{14} \text{ GeV}/m_x)$  or equal to that if these particles dominate cosmological dark matter.

The frozen number density of heavy particles can be estimated as

$$n_x/n_\gamma \sim \left[ V_x \sigma_x^{(ann)} m_x m_{Pl} \right]^{-1}, \quad (16)$$

where  $n_\gamma = 410/\text{cm}^3$  is the number density of CMBR photons,  $\sigma_x$  is the cross-section of  $x\bar{x}$ -annihilation and  $V_x$  is the c.m. velocity of  $x$ -particles. To satisfy the constraint (15) either the cross-section should be very large:

$$\sigma_x V_x > 10^{-38} \text{ cm}^2 = 10^{18} (m_x/10^{14} \text{ GeV}) \quad (17)$$

or the production of  $x$  in the early universe must be strongly suppressed, so the initial number density was much below the equilibrium value.

Interesting bounds on the properties of the super-heavy dark matter particles, come from consideration of the character of the density perturbations<sup>37</sup>. For non-equilibrium super-heavy dark matter isocurvature perturbations are non-negligible and since the latter are bounded by CMBR to be at most at the level of 10% with respect to the total density perturbations, this allows to conclude that  $m_x$  must be larger than the Hubble parameter at the end of inflation. Some model dependent bounds on the reheating temperature has been also derived<sup>37</sup>.

## 5. Conclusion

There is no compelling reason to expect that heavy quasi-stable particles exist. Of course grand unified theories (GUT) predict super-heavy gauge bosons with  $m_{GUT} \sim 10^{15} - 10^{16}$  GeV but they have very short life-time,  $\tau \sim (\alpha m_{GUT})^{-1}$ . Magnetic monopoles might exist but they should be absolutely stable. Stability of the Planck mass black holes is questionable. Thus, if heavy elementary particles exist they are most probably unstable. Stability could be ensured by a new symmetry and some conserved quantum numbers. However, a global symmetry, if broken by Planck scale physics, would not be able to make life-time sufficiently long. A new local symmetry, e.g. new QCD near the Planck scale could be broken very weakly, in contrast to global symmetries, and the life-time of  $x$  might be long.

With TeV gravity (quasi)stability is even more difficult to achieve but a new local symmetry with slightly massive gauge bosons could naturally allow for a large life-time.

It is difficult to confirm or reject the hypothesis of cosmological HqSP. Ultrahigh energy cosmic rays from their decay or annihilation could present a positive evidence if other possible explanations are excluded. It is even more difficult to establish if HqSP or some other objects make the bulk of cosmological dark matter. At the present day there are no definitive features in large scale structure or CMBR that could be reliably identified as signatures of heavy stable particles. Still though the chances are small the stakes are high. An importance of astronomical discovery of very heavy particles, inaccessible to existing accelerators even in foreseeable future, is difficult to overestimate.

## References

1. V. Berezhinsky, M. Kachelriess, A.Vilenkin, astro-ph/9708217, *Phys.Rev.Lett.* **79**, 4302 (1997);  
V.A. Kuzmin, V.A. Rubakov, astro-ph/9709187, *Phys. Atom. Nucl.* **61**, 1028 (1998), *Yad. Fiz.* **61**, 1122 (1998).
2. K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966);  
G.T. Zatsepin, V.A. Kuzmin, *JETP Lett.* **4**, 78 (1966) [*Pisma Zh. Eksp. Teor. Fiz.* **4**, 114 (1966)].
3. T. Stanev, astro-ph/0411113;  
G. Sigl, astro-ph/0404074, *Acta Phys. Polon.* **B35**, 1845 (2004);  
F.W. Stecker, astro-ph/0407311.
4. D.J.H. Chung, E.W. Kolb, A. Riotto, hep-ph/9805473, *Phys. Rev. Lett.* **81**, 4048 (1998); hep-ph/9810361.

5. F.C. Frank, *Nature*, 525 (1947)  
A.D. Sakharov, Lebedev Rep. (1948), see "Muon Catalyzed Fusion" (MCF) 4 (1989) 235.
6. V.A. Rubakov, *Pisma Zh. Eksp. Teor. Fiz.* **33** 658 (1981) [*JETP Lett.* bf 33, 644 (1981)].
7. N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, hep-ph/9803315, *Phys. Lett.* **B429**, 263 (1998).
8. S. Eidelman et al., *Phys. Lett.* **B592**, 1 (2004).
9. M.B. Voloshin, L.B. Okun, *Pisma Zh. Eksp. Teor. Fiz.* **28**, 156 (1978) [*JETP Lett.* **28**, 145 (1978)];  
L.B. Okun, Ya.B. Zeldovich, *Phys. Lett.* **B78**, 597 (1978).
10. T.D. Lee, C.N. Yang, *Phys. Rev.* **98**, 1501 (1955).
11. L.B. Okun, *Yad. Fiz.* **10**, 358 (1969).
12. A.D. Dolgov, *Phys. Repts.* **320**, 1 (1999).
13. Ya.B. Zeldovich, *Phys. Lett.* **A59**, 254 (1976).
14. F.C. Adams, G.L. Kane, M. Mbonye, M.J. Perry, hep-ph/0009154, *Int. J. Mod. Phys.* **A16**, 2399 (2001).
15. M.B. Voloshin, hep-ph/0107119, *Phys. Lett.* **B518**, 137 (2001); hep-ph/0111099, *Phys. Lett.* **B524**, 376 (2002).
16. C.T. Hill, *Nucl. Phys.* **B224**, 469 (1983).
17. V.K. Dubrovich, D. Fargion, M.Yu. Khlopov, hep-ph/0312105.
18. A.D. Dolgov, H. Maeda, T. Torii, hep-ph/0210267.
19. K. Yamamoto *Phys. Lett.* **B168**, 341 (1986);  
G. Lazarides, C. Panagiotakopoulos, Q. Shafi, *Phys. Rev. Lett.* **56**, 557 (1986);  
G.F. Giudice, A. Riotto, A. Zaffaroni, hep-ph/0408155.
20. T.W.B. Kibble, *Acta Phys. Polon.* **B13**, 723 (1982); T.W.B. Kibble, Proc. of NATO Advanced Study Institute, Cambridge 1994, Formation and interactions of topological defects 1-26, 1994.
21. S. Khlebnikov, L. Kofman, A. Linde, I. Tkachev, *Phys. Rev. Lett.* **81**, 2012 (1998);  
I. Tkachev, S. Khlebnikov, L. Kofman, A. Linde, *Phys. Lett.* **B440**, 262 (1998);  
S. Kasuya, M. Kawasaki, *Phys. Rev.* **D58**, 083516 (1988).
22. V.A. Kuzmin, I.I. Tkachev, *Phys. Rept.* **320**, 199 (1999).
23. V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, *Phys. Lett.* **B155**, 36 (1985).
24. A.D. Dolgov, hep-ph/9312208, *Nucl. Phys. Proc. Suppl.* **35**, 28 (1994).
25. L.F. Abbott, E. Farhi, M.B. Wise, *Phys. Lett.* **B117**, 29 (1982);  
A. Albrecht, P.J. Steinhardt, M.S. Turner, F. Wilczek, *Phys. Rev. Lett.* **48**, 1437 (1982);  
A. D. Dolgov, A. D. Linde, *Phys. Lett.* **B116**, 329 (1982).
26. A.D. Dolgov, D.P. Kirilova, *Yad. Fiz.* **51**, 273 (1990) [*Sov. J. Nucl. Phys.* **51**, 172 (1990)].
27. G.F. Giudice, M. Peloso, A. Riotto, I. Tkachev, *JHEP*, **9908**, 014 (1999).
28. J.H. Traschen, R.H. Brandenberger, *Phys. Rev.* **D42**, 2491 (1990).

29. L. Kofman, A.D. Linde, A.A. Starobinsky, *Phys. Rev. Lett.* **73**, 3195 (1994).
30. L. Parker, *Phys. Rev. Lett.* **21**, 562 (19680).
31. M.S. Chanowitz, J.R. Ellis, *Phys. Lett.* **B40**, 397 (1972).
32. A.D. Dolgov, *Pisma Zh. Eksp. Teor. Fiz.* **32**, 673 (1980);  
A.D. Dolgov, *Zh. Eksp. Teor. Fiz.* **81**, 417 (1981) [*Sov. Phys. JETP* **54**, 223 (1981)].
33. S.G. Mamamev, V.M. Mostepanenko, A.A. Starobinsky, *ZhETF*, **70**, 1577 (1976);  
V.M. Frolov, S.G. Mamaev, V.M. Mostepanenko, *it Phys. Lett.* **55A**, 389 (1976);  
A.A. Grib, S.G. Mamaev, V.M. Mostepanenko, *Gen. Relativity Grav.* **7**, 535 (1976).
34. A.A. Grib, S.G. Mamaev, V.M. Mostepanenko, *Vacuum Quantum Effects in Strong External Fields*, Friedmann Lab. Publ., St.-Petersburg, (1994).
35. V. A. Kuzmin, I. I. Tkachev, *JETP Lett.* **68**, 271 (1998);  
D.J.H. Chung, E.W. Kolb, A. Riotto, *Phys. Rev.* **D59**, 023501 (1999).
36. W.G. Unruh, *Phys. Rev.* **D14**, 870 (1976).
37. D.J.H. Chung, E.W. Kolb, A. Riotto, L. Senatore, astro-ph/0411468.